Colored scalars and proton destabilization

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Outline

- History of proton decay studies;
- SU(5) GUT model;
- Light colored scalars and low energy phenomenology;
- Light colored scalars in loop induced proton decay ;
- Higher dimensional operators;
- BNV at LHC?
- Summary and outlook.

Based on:

I.Doršner, S.F. J.F. Kamenik and N. Košnik, 0912.0972 ;
0906.5585; 1007.2604 ;
J. Drobnak, I.D., S.F., JFK, N.K. 1107.5393;
I.D., S.F., JFK, N.K., in preparation.

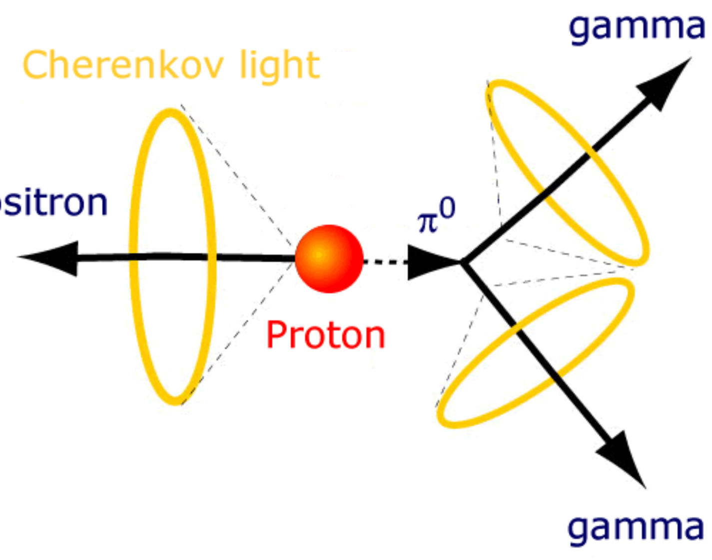
History of proton decay studies:

Theory: Law of baryon number conservation – Weyl et al. (1929-1949)

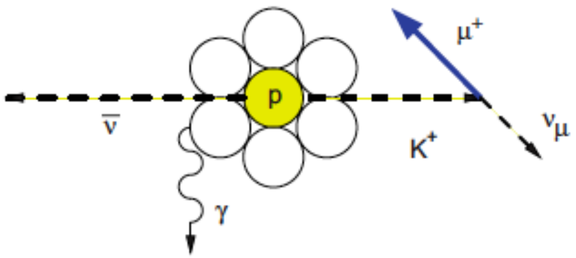
Experiment: Test of baryon number violation: Goldhaber in 1954
(lower limit $\tau > 1.4$ x10^{18}y);
Direct search : Reines et al. $\tau > 1$ x10^{22} y;

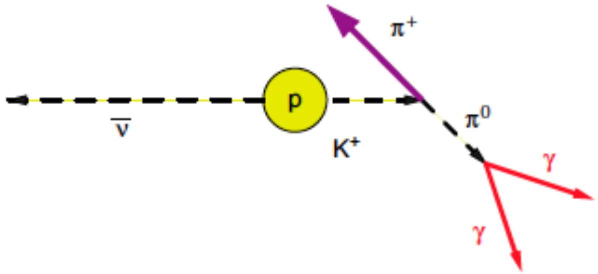
Further experimental searches: Kolar Gold Field,
NUSEX, FREJUS, SOUDAN,
tracking detectors

IMB and Kamiokande, Super-Kamiokande;
Cherenkov effect



Theory: Sakharov 1967- baryon asymmetry in the universe requires CP violation and baryon number non-conservation;
Pati-Salam 1973;
GUT non-super-symmetric, super-symmetric, supergravity,
Gravity (black holes and worm holes can catalyze proton decay)



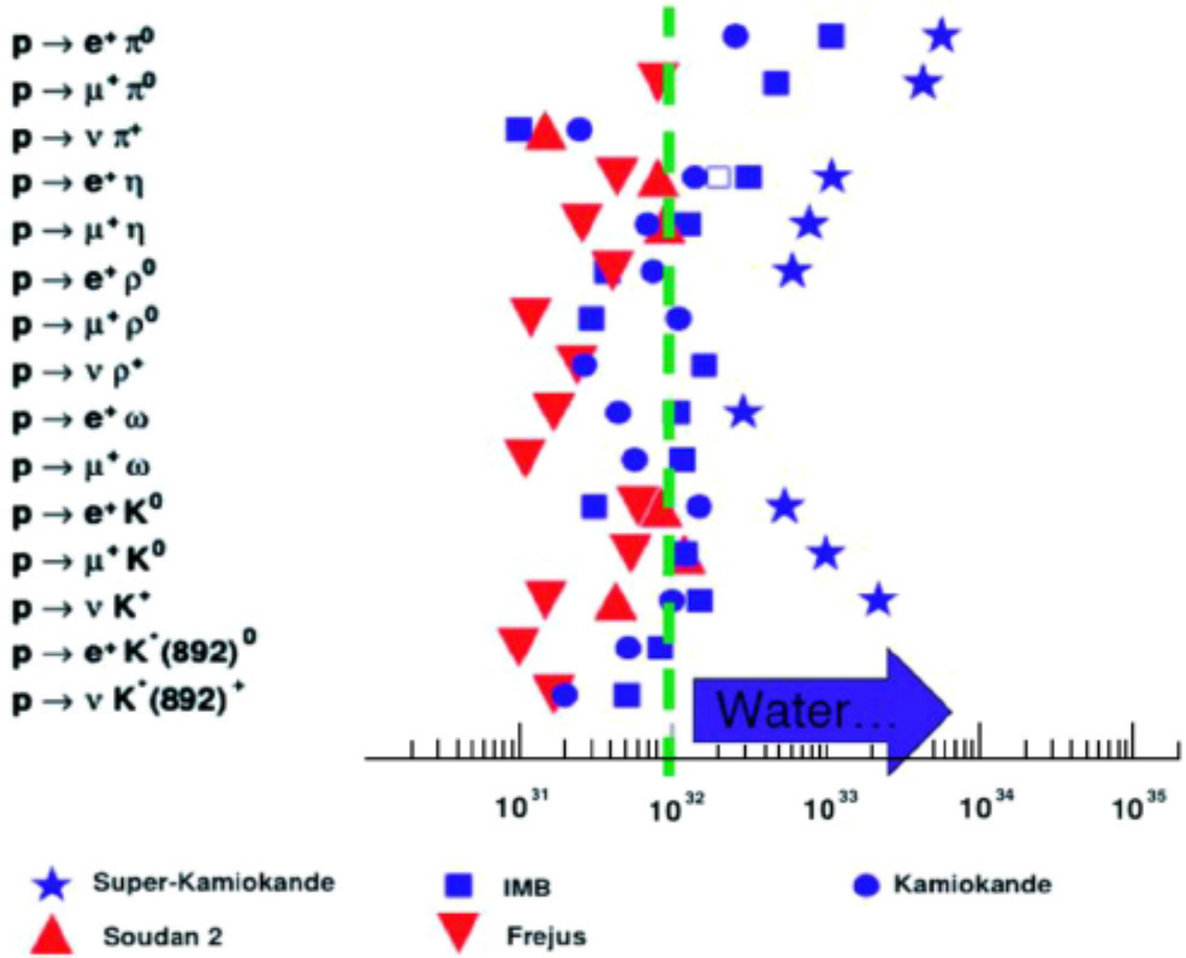


Super-Kamiokande experiment :
current limit on $p \to e^+ \pi^0$
$\tau > 8.2 \times 10^{33}$

PROCESS	τ_p (10^{33} years)	
$p \to \pi^0 e^+$	8.2	*
$p \to \pi^0 \mu^+$	6.6	
$p \to K^+ \bar{\nu}$	2.3	@
$p \to K^0 e^+$	1.0	
$p \to K^0 \mu^+$	1.3	
$p \to \eta e^+$	0.313	
$p \to \eta \mu^+$	0.126	
$p \to \pi^+ \bar{\nu}$	0.025	
⋮	⋮	
$p \to \pi^0 e^+$	13.0	¶
$p \to \pi^0 \mu^+$	11.0	
$p \to K^+ \bar{\nu}$	4.0	

*[Super-Kamiokande Collaboration], arXiv:0903.0676.
@[Super-Kamiokande Collaboration], arXiv:hep-ex/0502026.
¶ http://www.phys.utk.edu/blv2011/sessions01-06.html (Makoto Miura)

Next generation of proton decay experiments: $\tau > 4 \times 10^{34}$ years.
Future experiment: Hyper-Kamiokande



from Nath-Perez (2007)

GUT SU(5)

SM fermions

$$L_a \equiv (\mathbf{1}, \mathbf{2}, -1/2)_a = (\nu_a \quad e_a)^T$$

$$e^C_a \equiv (\mathbf{1}, \mathbf{1}, 1)_a$$

LEPTONS

$$(\mathbf{10}^{\alpha\beta})_a$$

$$Q_a \equiv (\mathbf{3}, \mathbf{2}, 1/6)_a = (u_a \quad d_a)^T$$

$$u^C_a \equiv (\overline{\mathbf{3}}, 1, -2/3)_a$$

QUARKS

$$(\overline{\mathbf{5}}_\alpha)_a$$

$$d^C_a \equiv (\overline{\mathbf{3}}, 1, 1/3)_a$$

$a = 1, 2, 3$
FAMILY INDEX

$\alpha, \beta = 1, 2, 3, 4, 5$
GROUP INDICES

*H. Georgi and S.L. Glashow (1974)

Fermion masses in SU(5) GUT

$$\underbrace{\mathbf{10} \times \overline{\mathbf{5}} = \mathbf{5} \oplus \mathbf{45}}_{M_D, M_E} \qquad \underbrace{\overline{\mathbf{5}} \times \overline{\mathbf{5}} = \overline{\mathbf{10}} \oplus \overline{\mathbf{15}}}_{M_N} \qquad \underbrace{\mathbf{10} \times \mathbf{10} = \overline{\mathbf{5}} \oplus \overline{\mathbf{45}} \oplus \overline{\mathbf{50}}}_{M_U}$$

5 15 45

$(\mathbf{10})_i(\overline{\mathbf{5}})_j\mathbf{5}^*$	$(\mathbf{10})_i(\overline{\mathbf{5}})_j\mathbf{45}^*$	$M_E,\ M_D$
$(\overline{\mathbf{5}})_i(\overline{\mathbf{5}})_j\mathbf{15}$		M_N
$(\mathbf{10})_i(\mathbf{10})_j\mathbf{5}$	$(\mathbf{10})_i(\mathbf{10})_j\mathbf{45}$	M_U

i,j- family index

Scalar in SU(5) $\rightarrow$ SU(3)xSU(2)xU(1)

$$\mathbf{5} = (D, T)$$

$$\begin{aligned} D &= (\mathbf{1}, \mathbf{2}, 1/2) \\ T &= (\mathbf{3}, \mathbf{1}, -1/3) \end{aligned}$$

$$\mathbf{45} = (\Delta_1, \Delta_2, \Delta_3, \Delta_4, \Delta_5, \Delta_6, \Delta_7)$$

$$\begin{aligned} \Delta_1 &= (\mathbf{8}, \mathbf{2}, 1/2) \\ \Delta_2 &= (\overline{\mathbf{6}}, \mathbf{1}, -1/3) \\ \Delta_3 &= (\mathbf{3}, \mathbf{3}, -1/3) \\ \Delta_4 &= (\overline{\mathbf{3}}, \mathbf{2}, -7/6) \\ \Delta_5 &= (\mathbf{3}, \mathbf{1}, -1/3) \\ \Delta_6 &= (\overline{\mathbf{3}}, \mathbf{1}, 4/3) \\ \Delta_7 &= (\mathbf{1}, \mathbf{2}, 1/2) \end{aligned}$$

Up-quarks

5 | 45

$$(Y_2')_{ij} 10_i 10_j 5 \qquad\qquad (Y_2)_{ij} 10_i 10_j 45$$

$$M_U = [\overbrace{4({Y_2'}^T + Y_2')v_5} - \overbrace{8(Y_2^T - Y_2)v_{45}}]/\sqrt{2}$$

$$\langle \mathbf{5} \rangle^5 = \sqrt{2} v_5$$

$$\langle \mathbf{45} \rangle_1^{51} = \langle \mathbf{45} \rangle_2^{52} = \langle \mathbf{45} \rangle_3^{53} = \sqrt{2} v_{45}$$

$$\Rightarrow$$

$$2|v_5|^2 + 48|v_{45}|^2 = v^2$$

$$v = 246\,\mathrm{GeV}$$

Down-quarks and charged lepton

$$(Y_1)_{ij} 10_i \bar{5}_j 45*$$

$$(Y_3)_{ij} 10_i \bar{5}_j 5*$$

$$M_E = 3Y_1^T v_{45}^* - \frac{1}{2} Y_3^T v_5^*$$

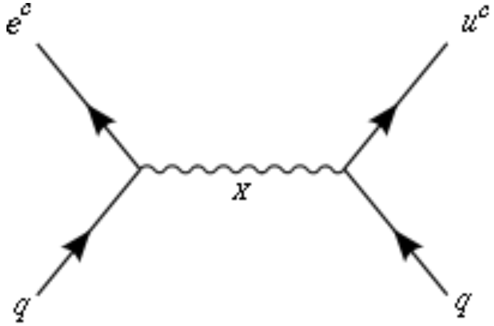
$$M_D = -Y_1 v_{45}^* - \frac{1}{2} Y_3 v_5^*$$

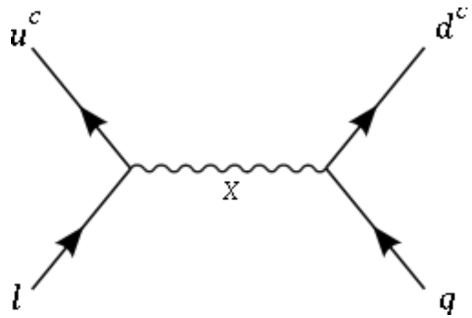
without 45: $M_E \approx M_D$ at GUT scale
with 45 : M_E= ≈ -3 M_D at GUT scale

Baryon number non-conservation: proton decay

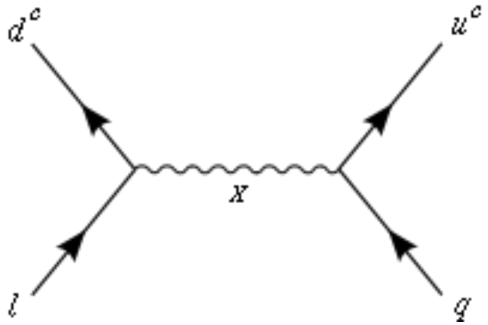
Minimal SU(5) contains in addition to SM gauge fields (12)
12 new gauge bosons X and Y

Vector gauge bosons mediation of proton decay





$M_X \approx 10^{15}$ GeV



dimension 6 operators

$$\frac{\overline{e^c u^c} qq}{\Lambda^2} \quad \frac{d^c d^c u^c e^c}{\Lambda^2} \quad \frac{qqql}{\Lambda^2} \quad \frac{\overline{d^c}\,\overline{u^c} ql}{\Lambda^2}$$

Scalars mediating proton decay

vector (gauge) leptoquarks ⟷ scalar leptoquarks

24 states

18 states — all of them either in SU(5) or flipped SU(5)

relevant decomposition of SU(5) to SM

$$SU(5) \rightarrow SU(3) \times SU(2) \times U(1)$$

$$\mathbf{5} = (\mathbf{1}, \mathbf{2}, 1/2) \oplus (\mathbf{3}, \mathbf{1}, -1/3);$$

$$\mathbf{10} = (\mathbf{1}, \mathbf{1}, 1) \oplus (\overline{\mathbf{3}}, \mathbf{1}, -2/3) \oplus (\mathbf{3}, \mathbf{2}, 1/6);$$

5,15 and 45 have electrically neutral state – can develop VEV

$$\mathbf{15} = (\mathbf{1}, \mathbf{3}, 1) \oplus (\mathbf{3}, \mathbf{2}, 1/6) \oplus (\mathbf{6}, \mathbf{1}, -2/3);$$

$$\mathbf{45} = (\mathbf{8}, \mathbf{2}, 1/2) \oplus (\overline{\mathbf{6}}, \mathbf{1}, -1/3) \oplus (\mathbf{3}, \mathbf{3}, -1/3) \oplus (\overline{\mathbf{3}}, \mathbf{2}, -7/6) \oplus (\mathbf{3}, \mathbf{1}, -1/3) \oplus (\overline{\mathbf{3}}, \mathbf{1}, 4/3) \oplus (\mathbf{1}, \mathbf{2}, 1/2);$$

$$\mathbf{50} = (\mathbf{8}, \mathbf{2}, 1/2) \oplus (\mathbf{6}, \mathbf{1}, 4/3) \oplus (\overline{\mathbf{6}}, \mathbf{3}, -1/3) \oplus (\overline{\mathbf{3}}, \mathbf{2}, -7/6) \oplus (\mathbf{3}, \mathbf{1}, -1/3) \oplus (\mathbf{1}, \mathbf{1}, -2).$$

Contributions of 5 and 45 give masses to u, d quarks and charged lepton.

Majorana neutrino gets mass from 15 (Dirac neutrino gets mass from 5.)

Scalar leptoquark that violate B and L are:

$$\boxed{(\mathbf{3},\mathbf{1},-1/3),\ (\mathbf{3},\mathbf{3},-1/3)\ \text{and}\ (\overline{\mathbf{3}},1,4/3)}$$

Comment: if one allows neutrino to be Dirac particle then from representation 10 one can get LQ violating B and L

$$(\overline{\mathbf{3}},1,-2/3)$$

Light scalars and GUT with 45

For the unification of SU(3)x SU(2)xU(1) within SU(5),
at one loop level, two equations should be satisfied:

$$\frac{B_{23}}{B_{12}} = \frac{5}{8}\frac{5\sin^2\theta_W - \alpha/\alpha_3}{3/8-\sin^2\theta_W} = 0.716 \pm 0.005,$$

$$B_{12} = \frac{16\pi}{5\alpha}(3/8-\sin^2\theta_W) = 184.9 \pm 0.2.$$

$$B_{ij} = B_i - B_j$$

$$B_i = \sum_I b_{iI} \ln M_{GUT}/m_I$$

$$(M_Z \leq m_I \leq M_{GUT})$$

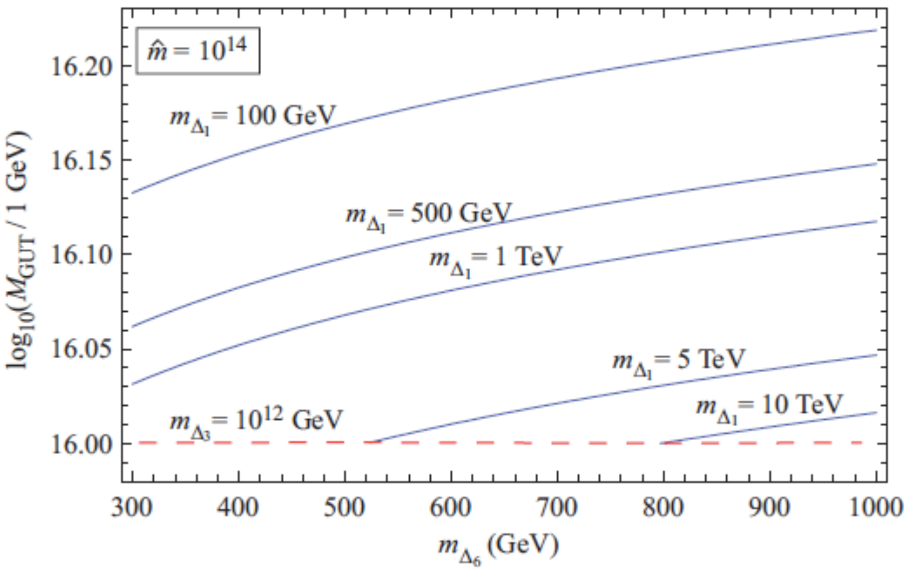
Input:

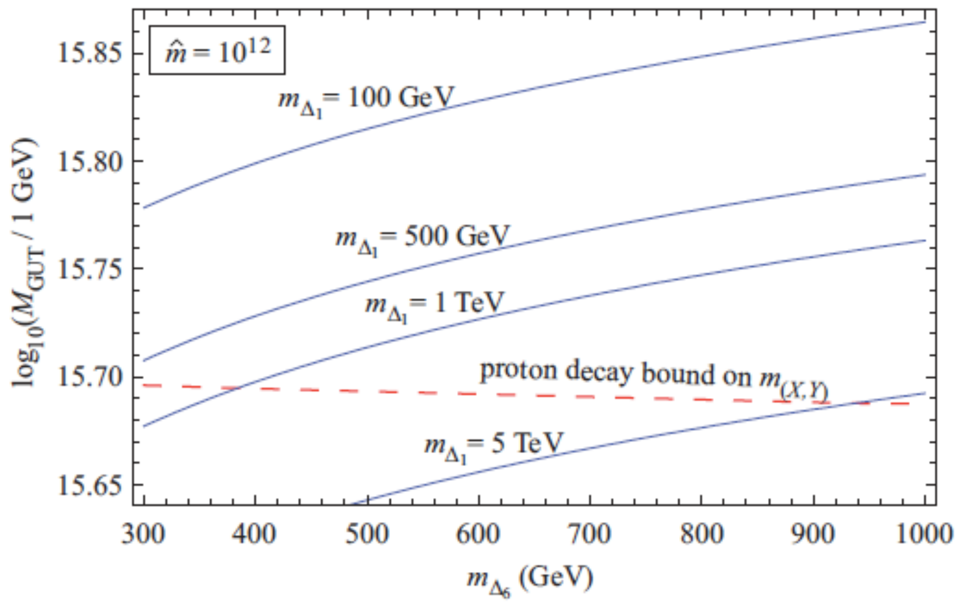
$$\alpha_3 = 0.1176 \pm 0.0020,\ \alpha^{-1} = 127.906 \pm 0.019$$

$$\sin^2\theta_W = 0.23122 \pm 0.00015$$

experimental result on proton lifetime: $\tau(p \to \pi^0 e^+) > 8.2 \times 10^{33}$ y

Can unification be achieved with light scalars?





Unification is possible if Δ_6 and Δ_1 are both relatively light.
It means if for $m_{\Delta 6} \approx 400$ GeV mass of the Δ_1 is above the 1 TeV!

Comment: If the partial lifetime of proton $p \to \pi^0 e^+$ is improved by factor 6
then $300\mathrm{GeV} \leq m_{\Delta_6} \leq 1\mathrm{TeV}$ ill be excluded.

In any scenario of NP one should consider all possible constraints from low energy phenomenology, collider physics and at higher scale (e.g. GUT scale)!

Flavor physics constraints on colored weak singlet scalar

- Forward-backward asymmetry in $\mathbf{t\bar{t}}$ production and diquark couplings of colored weak singlet scalar Δ;

- Diquark couplings in up-quark sector;

- Constraints on leptoquark down-quarks and lepton phenomenology;

- Role of $(g-2)_\mu$;

- Search for light Δ;

Light Δ_6 scalar

$(\mathbf{10}^{\alpha\beta})_i (\overline{\mathbf{5}}_\delta)_j \mathbf{45}^{*\,\delta}_{\alpha\beta}$

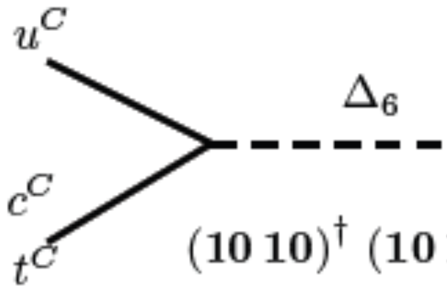
Δ_6

$\epsilon_{\alpha\beta\gamma\delta\epsilon} (\mathbf{10}^{\alpha\beta})_i (\mathbf{10}^{\zeta\gamma})_j (\mathbf{45})^{\delta\epsilon}_{\zeta}$

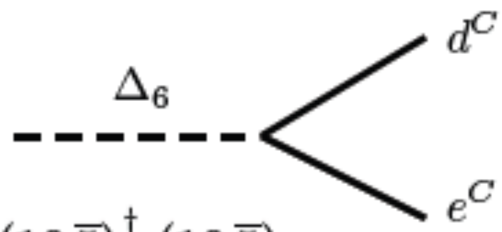
$(\overline{\mathbf{3}}, \mathbf{1}, 4/3)$

$$\frac{g_6^{ij}}{2} \epsilon_{abc} u^{C\,T}_{i\,a} C u^C_{b\,j} \Delta_{6\,c} \longleftarrow \boxed{(\mathbf{10}\,\mathbf{10}\,\mathbf{10}\,\overline{\mathbf{5}})} \longrightarrow Y_1^{ij} e^{C\,T}_i C d^C_{a\,j} \Delta^*_{6\,a}$$

$$g_6^{ij} = -g_6^{ji}$$



$(\mathbf{10}\,\mathbf{10})^\dagger\ (\mathbf{10}\,\mathbf{10})$



$(\mathbf{10}\,\overline{\mathbf{5}})^\dagger\ (\mathbf{10}\,\overline{\mathbf{5}})$

Forward-backward asymmetry in $t\bar{t}$ production and scalar triplet

Cross section measurements at Tevatron

$(\sqrt{s} = 1.96\ \mathrm{TeV})$

$$\sigma_{t\bar{t}}^{\mathrm{exp}} = 7.50 \pm 0.48\ \mathrm{pb}$$

[CDF note 9913,2009]

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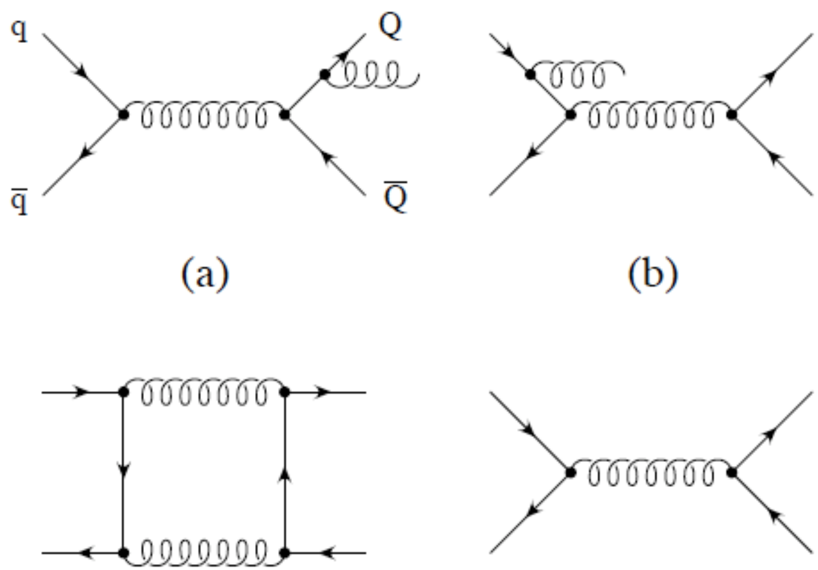
[CDF note 9913,2009]



(a) (b)

(c) (d)

SM prediction and experimental result agrees!

$$\sigma_{t\bar{t}}^{SM} = (7.22^{+0.31}_{-0.47}\,^{+0.71}_{-0.55})\ \mathrm{pb}$$

[Beneke et al, 2011]

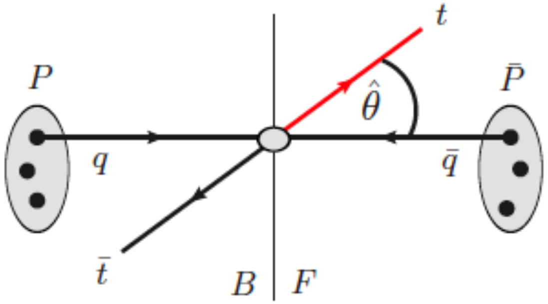
$$\sigma_{t\bar{t}}^{SM} = (6.30 \pm 0.19^{+0.31}_{-0.23})\ \mathrm{pb}$$

[Ahrens et al, 2010]

$$\sigma_{t\bar{t}}^{SM} = (7.46^{+0.66}_{-0.80})\ \mathrm{pb}$$

[Langenfeld et al, 2009]

Forward-backward asymmetry in double top production at Tevatron



$$A^t_{FB} = \frac{N_t(F) - N_t(B)}{N_t(F) + N_t(B)}$$

$M_{t\bar{t}}$ dependence of A_{FB}

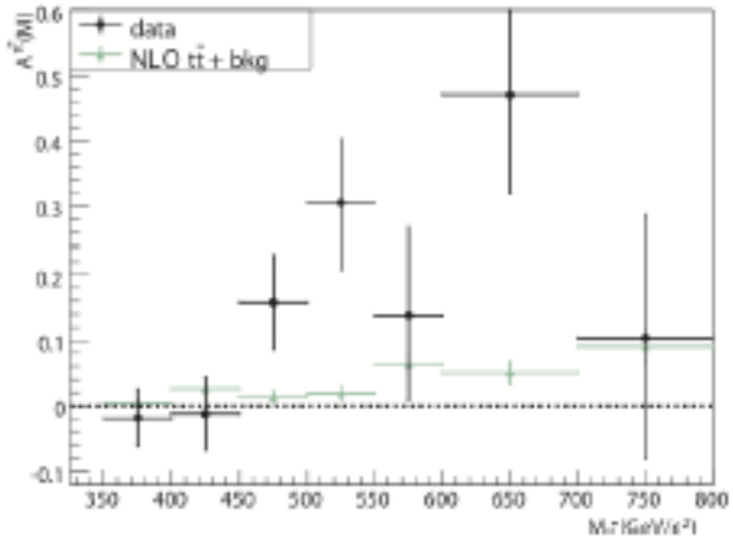
$$A^t_{FB} = \begin{cases} 0.158 \pm 0.072 \pm 0.017 \;\; (CDF) \\ 0.42 \pm 0.15 \pm 0.05 \;\; (CDF) \\ 0.196 \pm 0.060^{+0.018}_{-0.026} \;\; (D0) \end{cases}$$

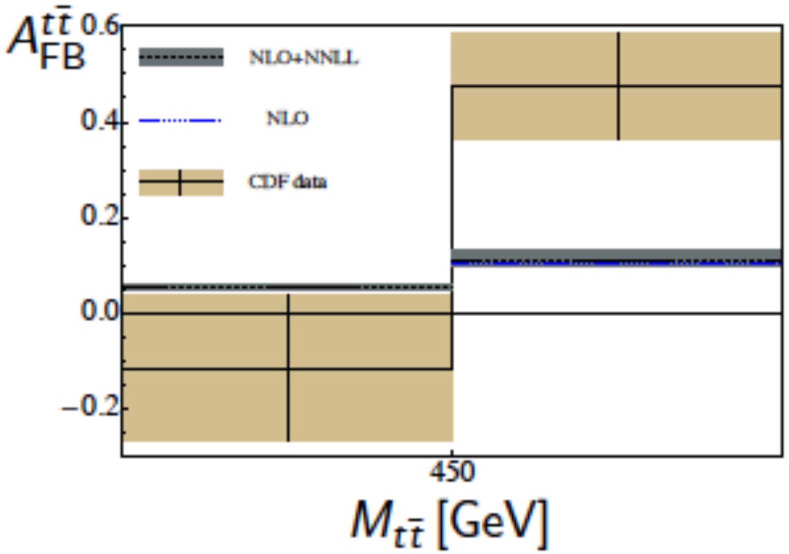
SM A_{FB} at NNLO QCD

$$(7.24^{+1.04+0.20}_{-0.67-0.27}) \cdot 10^{-2}$$

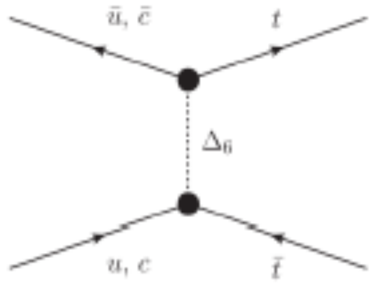
V. Ahrens et al, 2011;

$$A^t_{FB} \simeq 0.200 \pm 0.047$$





A_{FB} at Tevatron and Δ_6 exchange in u-channel



$$\frac{d\sigma^{q\bar{q}}(\hat{s})}{d\hat{t}} = \frac{d\sigma^{q\bar{q}}_{SM}(\hat{s})}{d\hat{t}} \underbrace{\boxed{-\frac{\alpha_s |g_{qt}|^2}{9\hat{s}^3}\frac{m_t^2\hat{s} + (m_t^2 - \hat{u})^2}{m_\Delta^2 - \hat{u}}}}_{\Delta\times\text{SM interference term}} + \frac{|g_{qt}|^4}{48\pi\hat{s}^2}\frac{(m_t^2 - \hat{u})^2}{(m_\Delta^2 - \hat{u})^2}$$

$$\hat{t} = (p_u - p_t)^2$$

$$\hat{u} = (p_{\bar{u}} - p_t)^2$$

moderate increase of σ by Δ, while it enhances A_{FB}

best fit value for $\boxed{|g_{ut}| = 0.9(2) + 2.5(4)\frac{m_\Delta}{1\ \text{TeV}}}$

preferred value
$m_\Delta \approx 400$ GeV

Our recent fit of SM + NP:
(S.F., J.F.K., B.M. in preparation)

forward-backward asymmetry, charge asymmetry at Atlas,
cross-section at Tevatron

A: $m_{t\bar{t}} \in [700, 800]$ GeV next-to-last bin $\sigma^h_{\mathrm{TEV}} = (80 \pm 0.37)$ fb

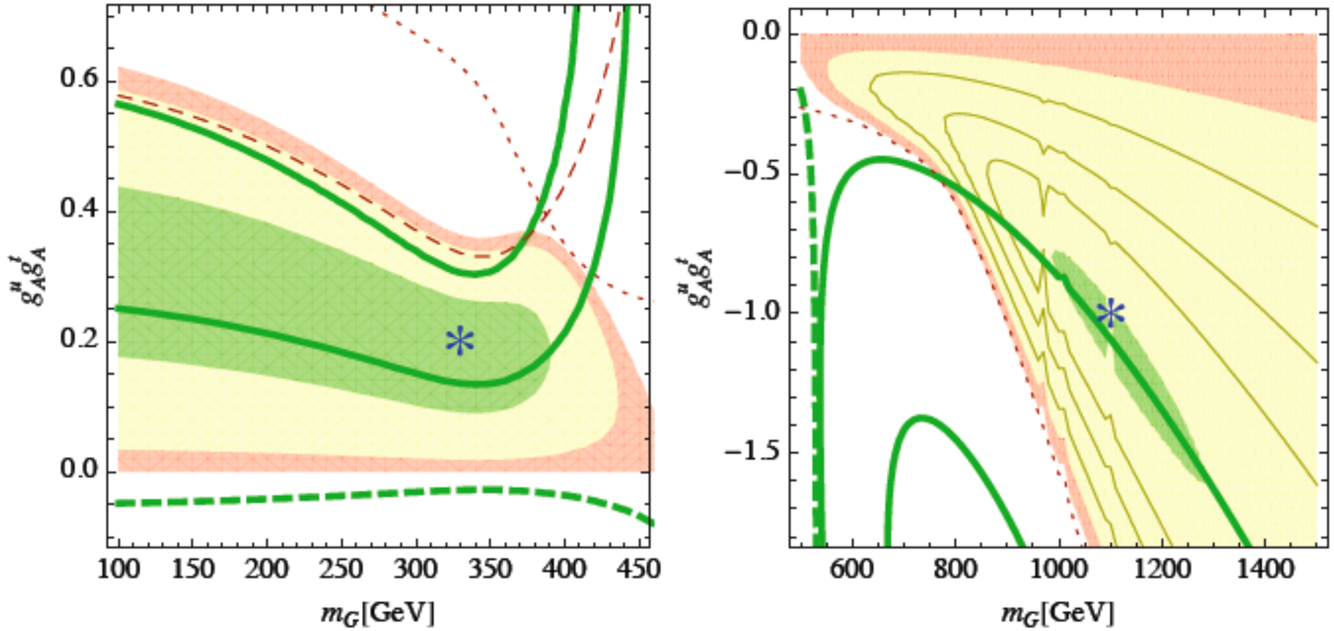
B: $m_{t\bar{t}}$ bin spectrum at CDF, no cross - section

existing scenarios:

- axigluon → s-channel
- color triplet → u-channel
- color sextet
- doublet
- W'
- Z'

(color sextet, doublet, W', Z') → t-channel

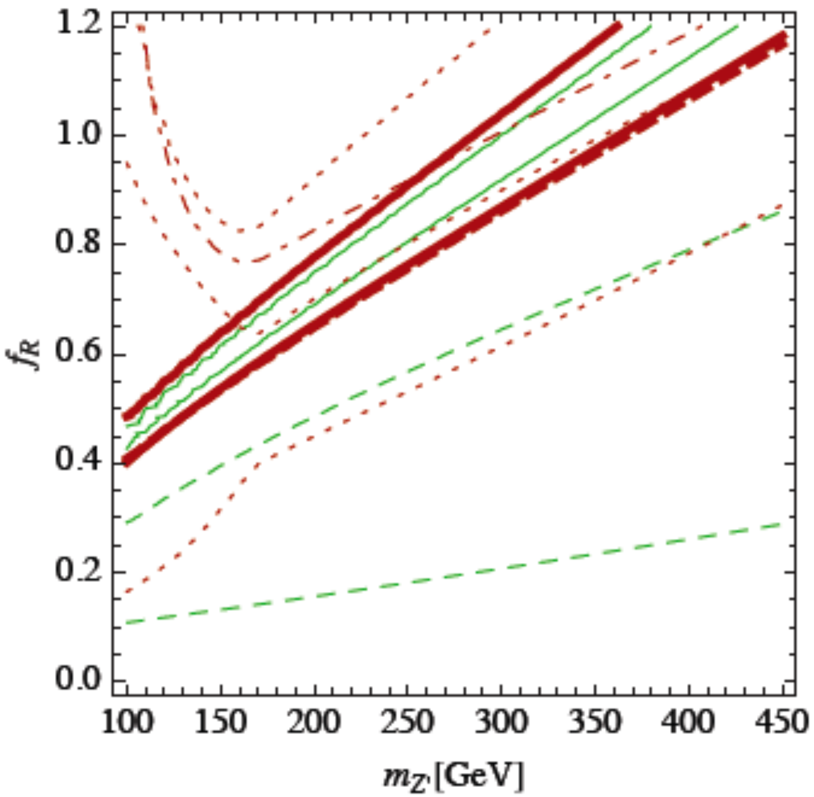
Axigluon



"G low mass"	$m_G = 330$ GeV ,	$g_A^u g_A^t = 0.2$,
"G high mass"	$m_G = 1100$ GeV ,	$g_A^u g_A^t = -1.0$.

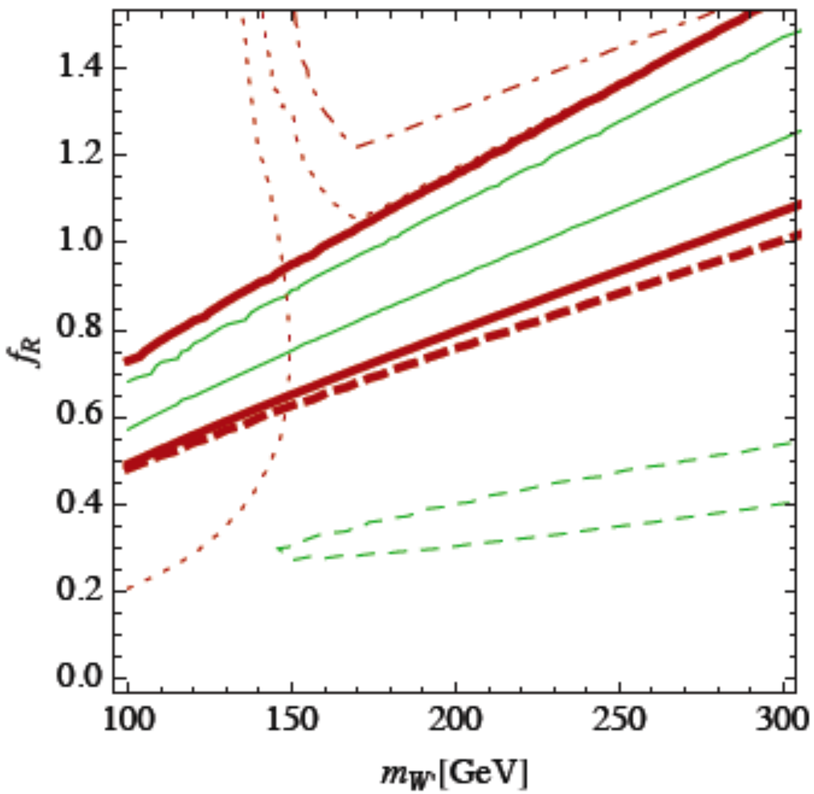
e.g. G. M. Tavares and M. Schmaltz, Phys. Rev. D **84**, 054008 (2011) [arXiv:1107.0978 [hep-ph]]

Z’



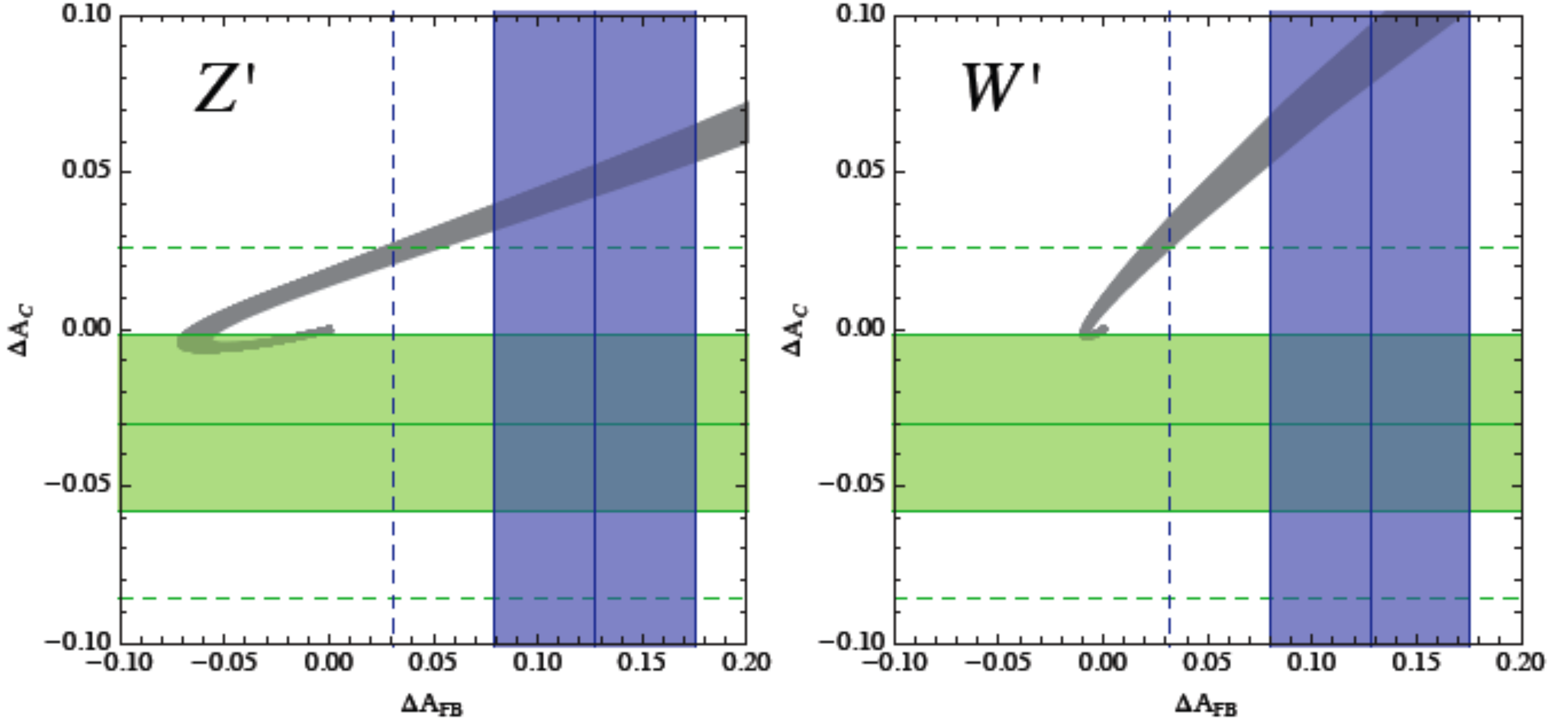
100 GeV ≤ $m_{Z'}$ ≤ 400 GeV

W’



100 GeV ≤ $m_{W'}$ ≤ 400 GeV

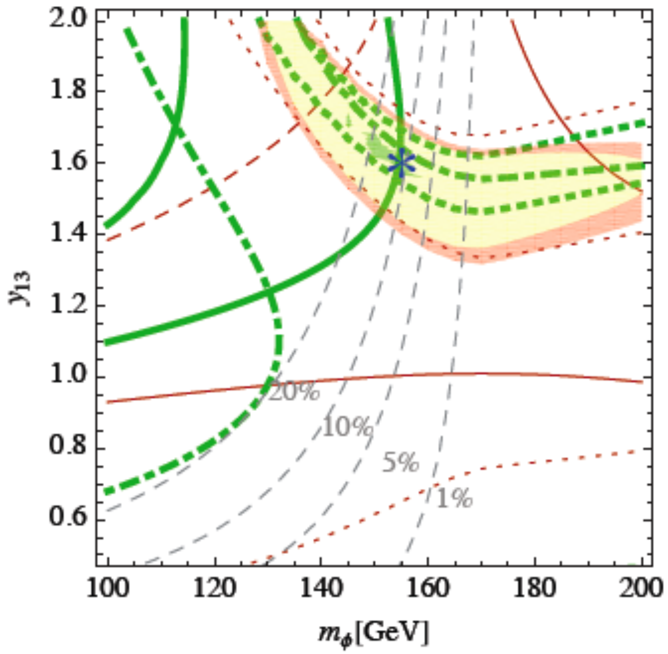
Tension between A_{FB} and A_C



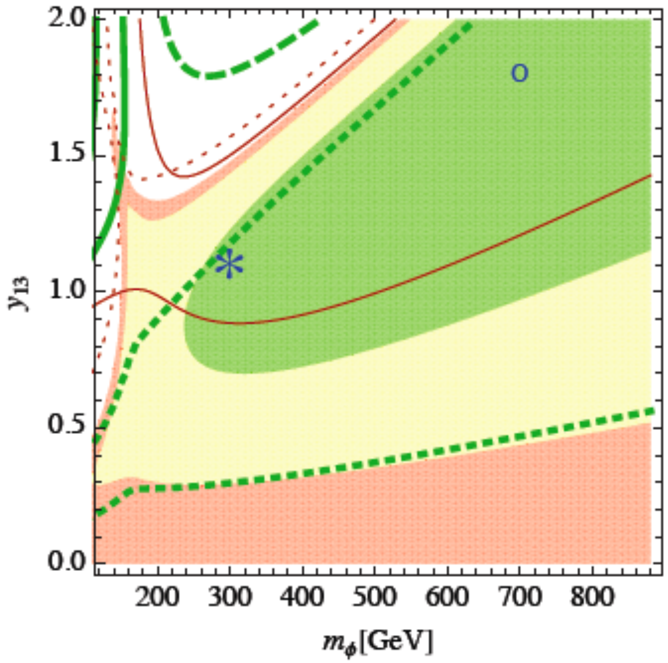
$100\text{ GeV} \leq m_{Z'} \leq 400\text{ GeV}$ $\quad$ $100\text{ GeV} \leq m_{W'} \leq 400\text{ GeV}$

Scalar iso-doublet

A



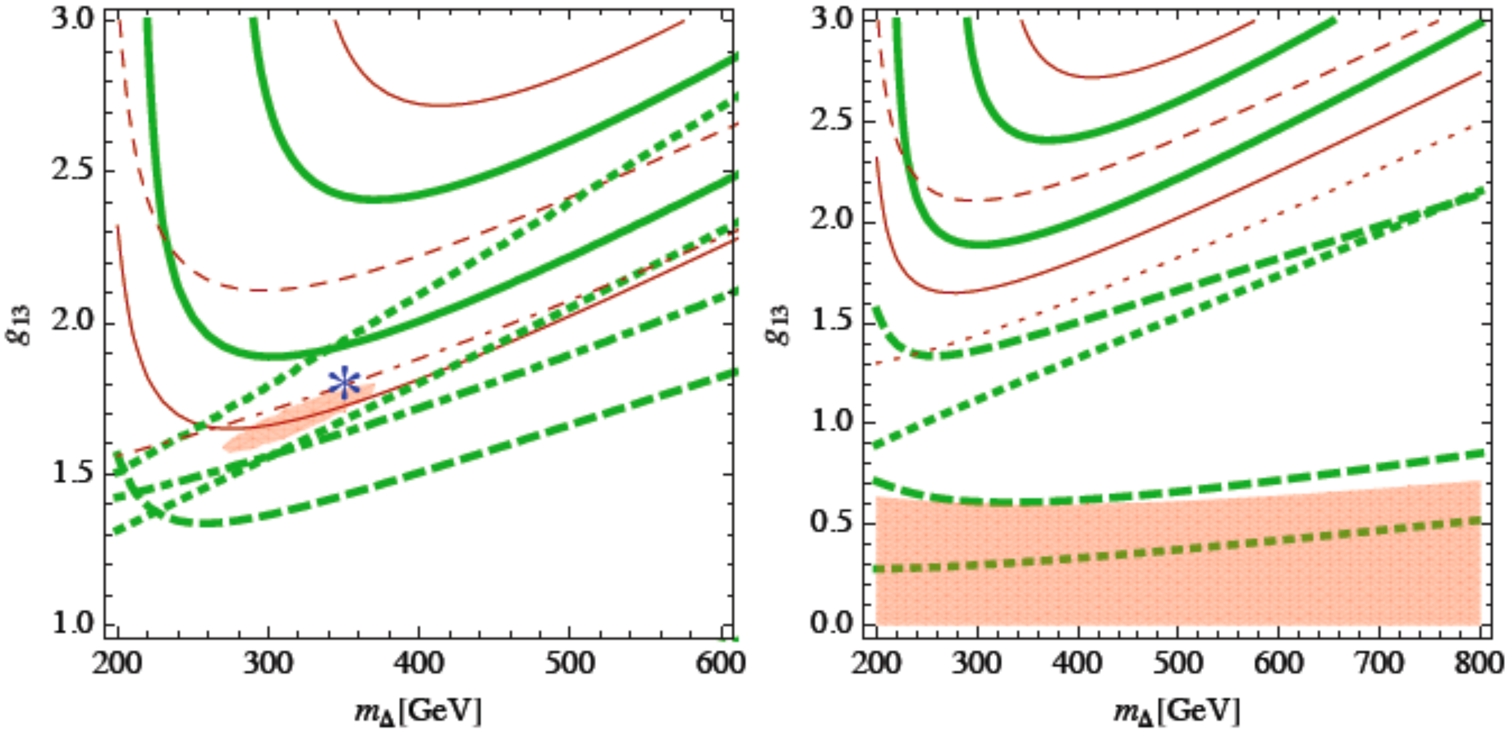
B



"ϕ low mass"	$m_\phi = 155$ GeV ,	$y_{13} = 1.6$
"ϕ intermediate mass"	$m_\phi = 300$ GeV ,	$y_{13} = 1.1$
"ϕ high mass"	$m_\phi = 700$ GeV ,	$y_{13} = 1.8$

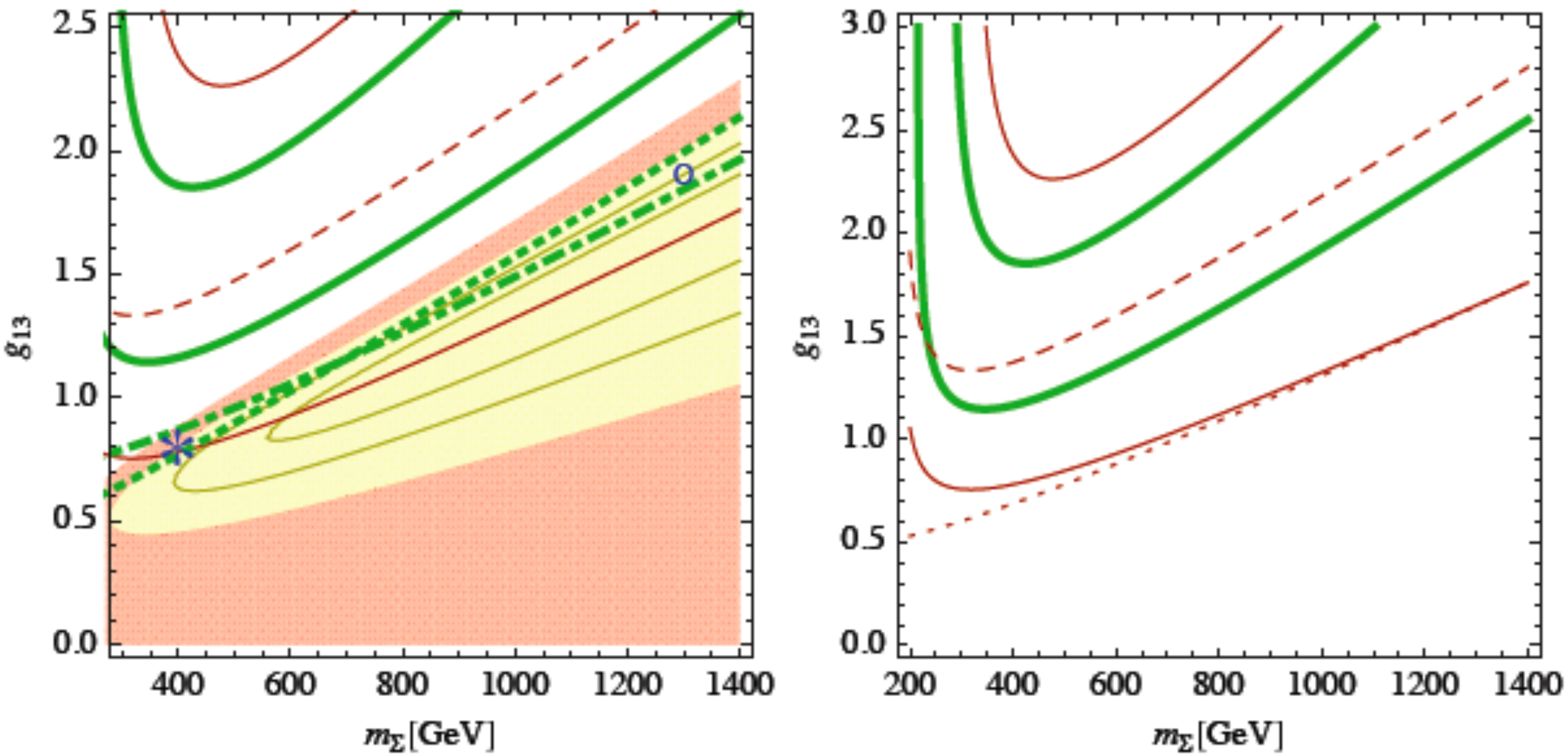
K. Blum, Y. Hochberg and Y. Nir, JHEP **1110**, 124 (2011) [arXiv:1107.4350 [hep-ph]]

Color triplet



"Δ" $m_\Delta = 350$ GeV , $g_{13} = 1.8$

Color sextet



"Σ low mass"	$m_\Sigma = 400$ GeV,	$g_{13} = 0.8$.
"Σ high mass"	$m_\Sigma = 1300$ GeV,	$g_{13} = 1.9$.

Viable NP scenarios explaining observed anomaly top – anti-top production:

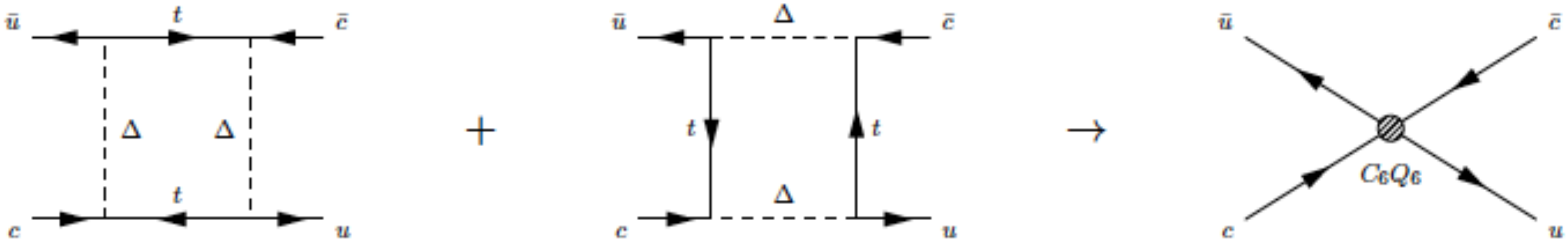
axigluon, scalar doublet in the both cases A and B, colored triplet and sextet are good candidate for NP in the case B (the CDF result on invariant mass spectrum is not taken into account)!

The goal of our study: to systematically investigate **triplet scalar** in GUT SU(5)

$$\mathcal{L}_\Delta = Y_{ij}\bar{\ell}_i P_L d^C_{ja}\Delta^{a*} + \frac{g_{ij}}{2}\epsilon_{abc}\bar{u}_{ia}P_L u^C_{jb}\Delta^c + \mathrm{h.c.}$$

Color triplet (diquark) couplings in up-quark sector

$$D^0 - \bar{D}^0$$



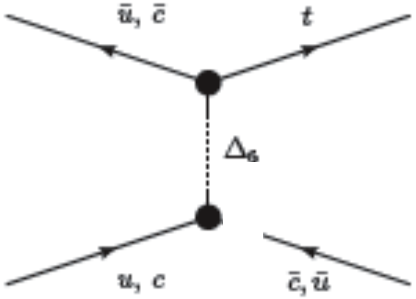
Δ contributes to $M_{12} = \langle D^0 \,|\, \mathcal{H}_{\rm eff} \,|\, \bar{D}^0 \rangle /(2m_D)$

$$x_{12} = \frac{2|M_{12}|}{\Gamma}, \qquad y_{12} = \frac{|\Gamma_{12}|}{\Gamma}, \qquad \phi_{12} = \arg(M_{12}/\Gamma_{12})$$

HFAG 2010 $\left\{ \begin{array}{c} x = 90.59 \pm 0.20)\%, \;\; y = (0.81 \pm 0.13)\% \\ |q/p| = 0.98^{+0.15}_{-0.14}, \;\; \Phi = -0.051^{+0.1112}_{-0.115}. \end{array} \right\}$

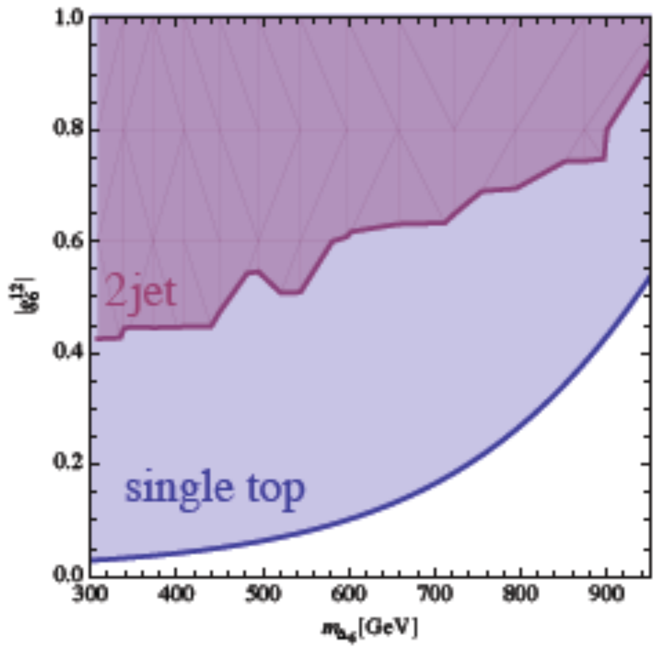
- in SM CP violating phase consistent with 0;
- x is in SM prediction range- long distance contribution dominant!

$$g_{ct} \leq few \;\; 10^{-3}$$



Single top production

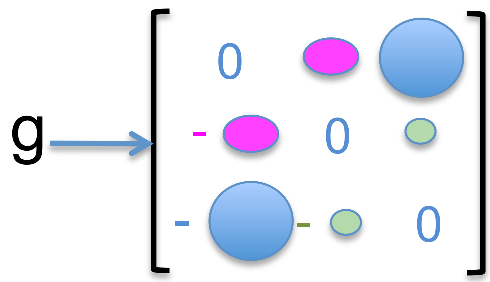
$$\frac{d\sigma^{u\bar{u}\to t\bar{c}}}{d\hat{t}} = -\frac{|g^*_{ut}g_{uc}|^2}{48\pi\hat{s}^2}\frac{(\hat{s}+\hat{t})\hat{u}}{(\hat{u}-m^2_\Delta)^2+\Gamma^2_\Delta}$$
$$+\ \text{s–channel}$$



we require

$$\Delta\sigma 1t \leq 1\ \ pb\ \ at\ \ 95\%\ \ CL$$

$g_{uc} \approx 0.1$

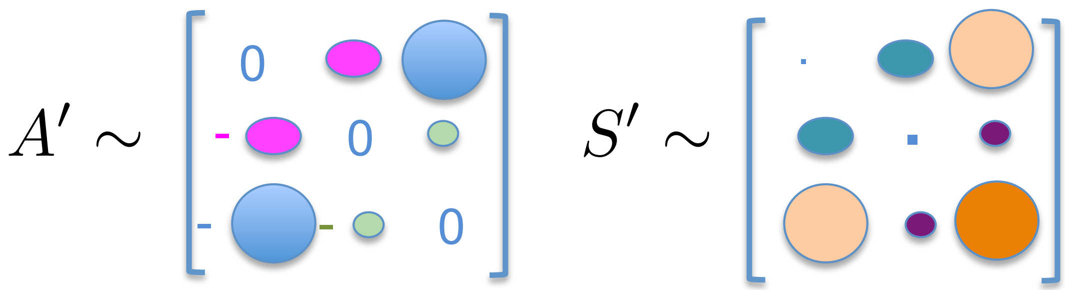


$$M_U = \left[4\underbrace{(Y_2'^T + Y_2')}_{\text{symmetric}}v_5 - 8\underbrace{(Y_2^T - Y_2)}_{\text{anti-symmetric}}v_{45}\right]/\sqrt{2},$$

$$4S' = U^\dagger M_U^{diag} + M_U^{diag} U^*$$
$$4A' = U^\dagger M_U^{diag} - M_U^{diag} U^*,$$

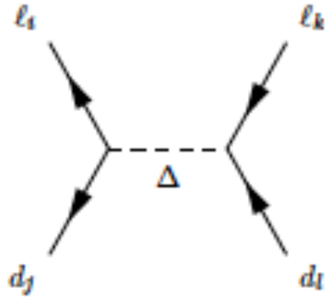
diagonal up-quark mass matrix

Lopsided structure of the mass matrix!

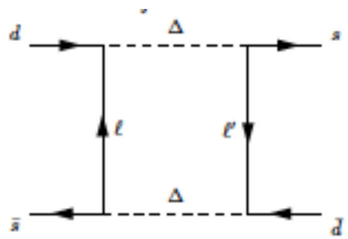


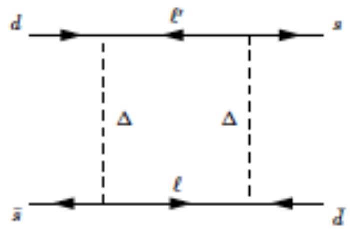
Down-quarks and leptons interactions with Δ

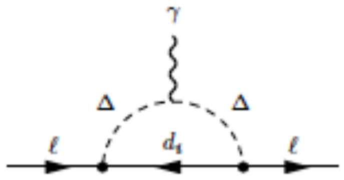
$$\mathcal{L}_{\Delta} = Y_{ij} \bar{l}_i P_L d_{ja} \Delta_a^*$$

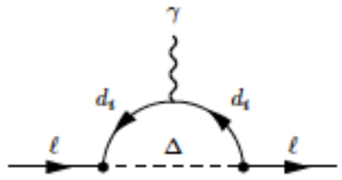


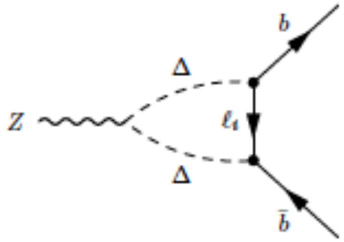
$$\mathcal{H}^{\Delta}_{d_i \bar{d}_j \to \ell_a^- \ell_b^+} = \frac{Y_{aj} Y_{bi}^*}{2 m_\Delta^2} (\bar{\ell}_a \gamma^\mu P_R \ell_b)(\bar{d}_j \gamma_\mu P_R d_i)$$

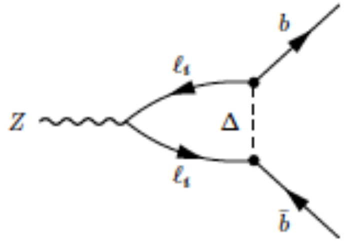












Enough variables to (over)constrain Y

Constraints at tree level

- LFV meson decays to leptons, semileptonic decays

$$K^0 \to \ell\ell', \; B_{d(s)} \to \ell\ell',$$
$$B \to X_s \ell^+\ell^-, \; B \to K(\pi)\ell\ell'$$

- μ–e conversion in nuclei
- LFV decays of τ

$$\tau \to e\pi^0, \; \tau \to eK_S, \ldots$$

Loop processes

- K and B physics

$$\epsilon_K, \; \Delta m_s, \; \Delta m_d, \; \boxed{\sin 2\beta_s}, \; \sin 2\beta$$

- anomalous magnetic moments

$$\boxed{(g-2)_\mu}, \; (g-2)_e$$

- LFV radiative decays

$$\mu \to e\gamma, \; \tau \to \mu\gamma, \; \tau \to e\gamma$$

- decays of $Z \to b\bar{b}$

Anomalous lepton magnetic moment

$$\mathcal{A}^\mu \equiv -ie\bar{u}(p',s')\Gamma^\mu u(p,s)\,,$$

$$\Gamma^\mu = F_1\gamma^\mu + \frac{F_2}{2m_\mu} i\sigma^{\mu\nu}q_\nu + F_3\sigma^{\mu\nu}q_\nu\gamma_5 + F_4(2mq^\mu + q^2\gamma^\mu)\gamma_5$$

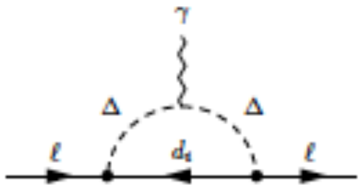
$$a_\mu = (g-2)_\mu/2 = F_2(q^2=0)$$

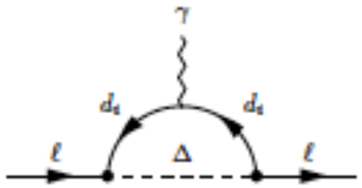
SM: QED + hadronic vacuum polarization + weak corrections

$$a_\mu^{\rm exp} = 1.16592080(63)\times 10^{-3} \qquad \text{[Bennet et al]}$$

$$a_\mu^{\rm SM} = 1.16591793(68)\times 10^{-3} \qquad \text{[Jegerlehner]}$$

$$\Rightarrow \quad \delta a_\mu = a_\mu^{\rm exp} - a_\mu^{\rm SM} = (2.87 \pm 0.93)\times 10^{-9}$$





Δ provides $a_\mu^\Delta > 0$

$$a_\mu^\Delta = \frac{3m_\mu^2}{16\pi^2 m_\Delta^2}\sum_{i=d,s,b}|Y_{\mu i}|^2\left[Q_\Delta f_\Delta(x_i) + Q_d f_d(x_i)\right], \qquad x = m_{d_i}^2/m_\Delta^2$$

Puzlle: does Δ provide missing part of a_μ and hides effects in LFV and FCNC?

CP phase in B_s system

$$\Delta M_s \equiv M_{sH} - M_{sL}$$ very accurately measured

$$\Delta\Gamma_s \equiv \Gamma_{sL} - \Gamma_{sH}$$

$$\Delta M_s = (17.73 \pm 0.05)\,\mathrm{ps}^{-1} \qquad (\Delta M_s)_{\mathrm{SM}} = (17.3 \pm 2.6)\,\mathrm{ps}^{-1}$$

-

$$B_s \to J/\psi\phi$$

$$(\phi^s_{J/\psi\phi})_{\mathrm{SM}} = \arg\left[\frac{(V^*_{ts}V_{tb})^2}{(V^*_{cs}V_{cb})^2}\right] = (-2.1 \pm 0.1)^\circ \qquad (\Delta\Gamma_s)_{\mathrm{SM}} = (0.087 \pm 0.021)\,\mathrm{ps}^{-1}$$

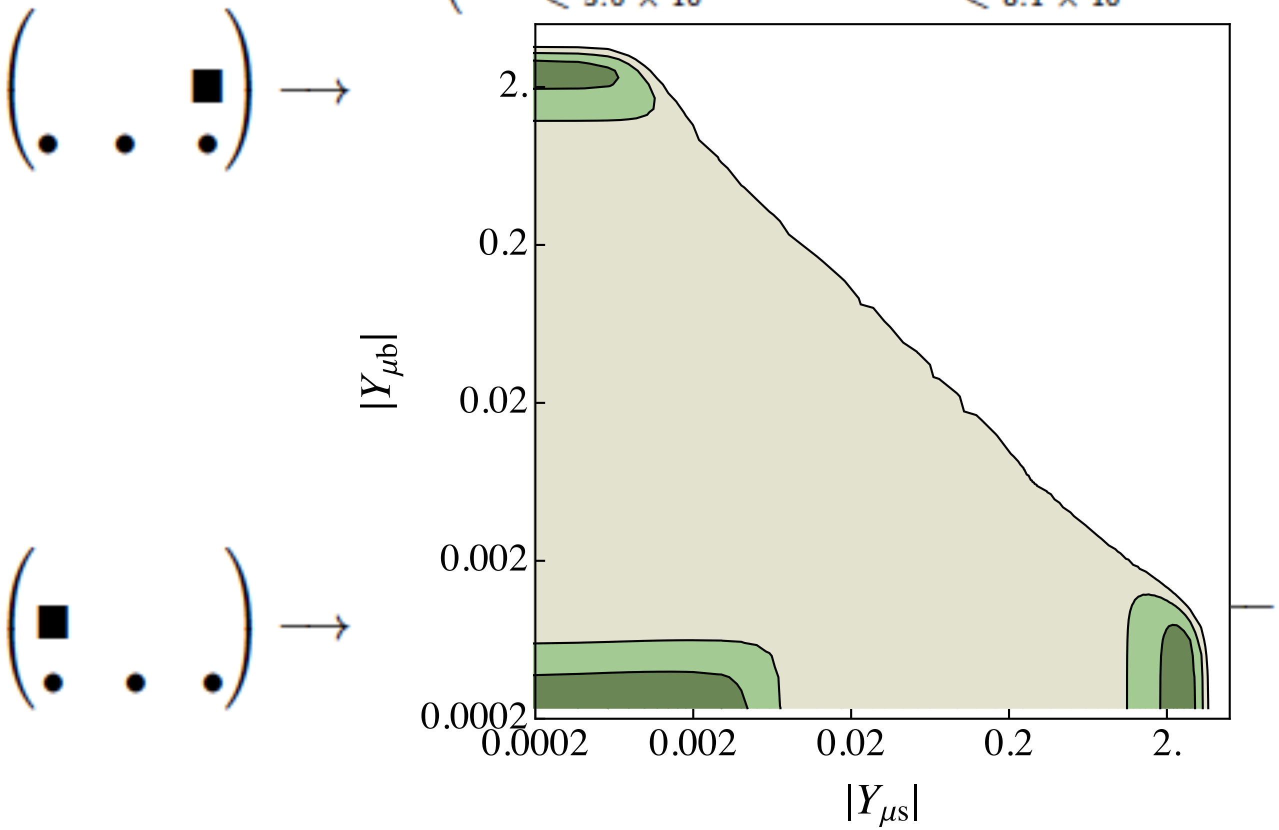
slight tension SM and experimental results

CDF and D0 $\phi^s_{J/\psi\phi} = (-32 \pm 18)^\circ \qquad \Delta\Gamma_s = (0.097 \pm 0.032)\,\mathrm{ps}^{-1}$ at 68% CL

LHCb $\phi^s_{J/\psi\phi} = (1.7 \pm 10.0)^\circ\,, \qquad \Delta\Gamma_s = (0.123 \pm 0.030)\,\mathrm{ps}^{-1}\,.$

Global fit of leptoquark couplings

$$|Y^{(1\sigma)}| \in \begin{pmatrix} < 1.4\times10^{-6} & < 8.7\times10^{-5} & < 4.1\times10^{-4} \\ < 3.6\times10^{-3}\cup[2.1,2.9] & < 3.6\times10^{-3}\cup[2.1,2.9] & < 6.2\times10^{-4}\cup[2.2,2.8] \\ < 5.6\times10^{-3} & < 8.1\times10^{-3} & < 9.6\times10^{-3} \end{pmatrix}$$



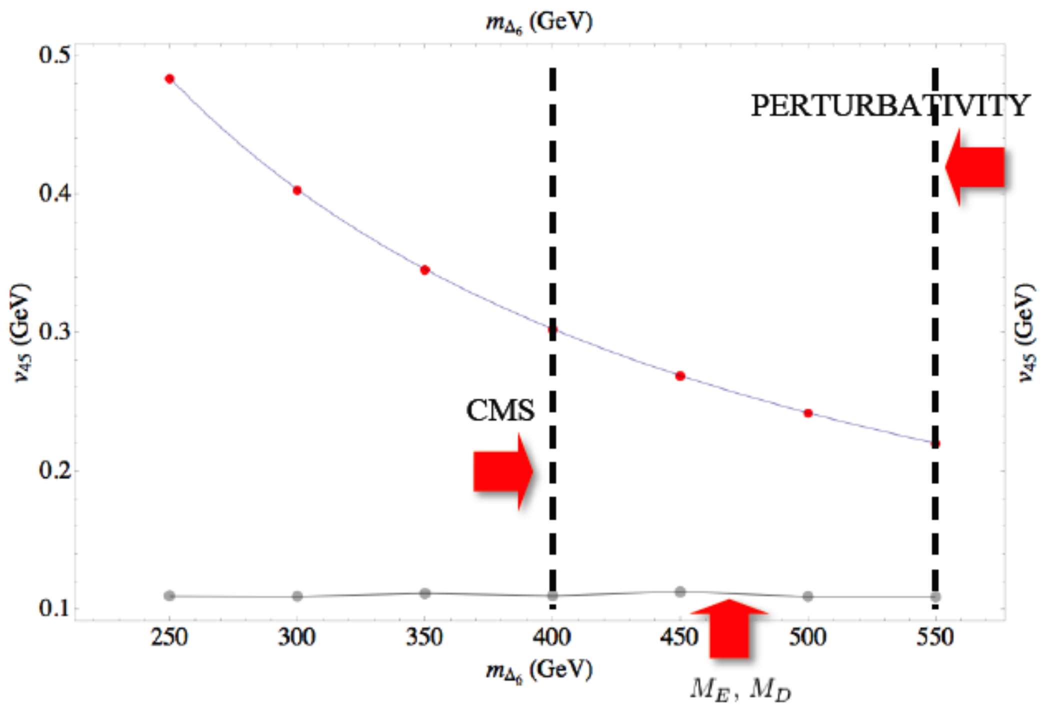
$(g\text{-}2)_\mu$ most important in the fit

Yukawa couplings of down quarks and leptons

After having all phenomenological constraints, numerical study of mass relation implies:

$$E_R^\dagger D_L M_D^{\rm diag} - M_E^{\rm diag} E_L^T D_R^* = -4 Y_1 v_{45} \Rightarrow \underbrace{\begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ \blacksquare & \blacksquare & \blacksquare \end{pmatrix}}_{m_\tau} + \underbrace{\begin{pmatrix} 0 & 0 & \bullet \\ 0 & 0 & \bullet \\ 0 & 0 & \bullet \end{pmatrix}}_{m_b}$$

One gets that in potentially viable scenario (23) element dominant, however, due to $m_\tau(M_{\rm GUT}) \sim 2 m_b(M_{\rm GUT})$ |33|>|23|, what cannot be satisfied in this SU(5)model.



Solution: Instead of simple SU(5) GUT

SO(10) scenario with scalars in 10, 120 and $\overline{126}$

$$E_R^\dagger D_L M_D^{\mathrm{diag}} - M_E^{\mathrm{diag}} E_L^T D_R^* = -4 E_R^\dagger Y_{126} D_R^* v_{126} + 4 E_R^\dagger Y_{120} D_R^* v_{120}''$$

Mass relation gets an additional term!

Proton decay in SU(5) GUT with the light Δ in 45

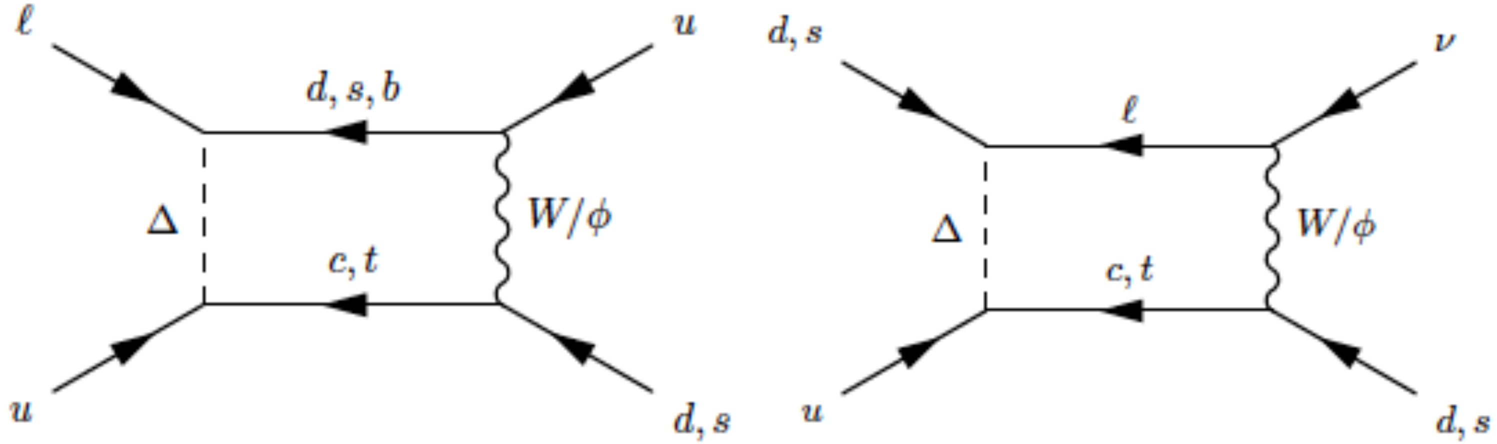
Due to asymmetry of g there is no possibility for proton to decay at tree level!
(u-t; u-c, t-c, transitions only)

$$\mathcal{L} = \sqrt{2}\epsilon_{abc}\overline{u_a}\overbrace{\left[U_R^\dagger(Y^{10}-Y^{10T})U_R^*\right]}^{\text{remains anti-symmetric}} P_L u_b^C\,\Delta_c + \sqrt{2}\epsilon_{abc}\overline{u_a^C}\left[U_R^T(Y^{10*}-Y^{10\dagger})U_R\right] P_R u_b\,\Delta_c^*$$
$$-\bar{\ell}\left[E_R^\dagger Y^{\bar{5}} D_R^*\right] P_L d_a^C\,\Delta_a^* - \overline{d_a^C}\left[D_R^T Y^{\bar{5}\dagger} E_R\right] P_R \ell\,\Delta_a\,.$$

transition from the weak to mass base

Comment: in SO(10) 45 representation of SU(5) can be found in 120 and 126
(120 anti-symmetric , 126-symmetric couplings to matter fields)
In 120 then there is the same absence of proton decay, while in the 126 couplings to
up-quarks should be set to 0.

Box-diagram contribution to proton decay



Amplitudes :

$$\frac{iG_F}{8\pi^2}\left[U_C^\dagger(Y^{10*}-Y^{10\dagger})U_C^*\right]_{ui}V_{id}V_{uj}^*\left[D_C^\dagger Y^{\bar{5}\dagger}E_C^*\right]_{j\ell}J(x_\Delta,x_{u_i},x_{d_j})\,\epsilon_{abc}\left(\overline{u_a^C}\gamma^\mu P_L d_b\right)\left(\overline{\ell^C}\gamma_\mu P_L u_c\right)$$
$$\frac{iG_F}{8\pi^2}\left[U_C^\dagger(Y^{10*}-Y^{10\dagger})U_C^*\right]_{ui}V_{id}\left[D_C^\dagger Y^{\bar{5}\dagger}E_C^*\right]_{d\ell}J(x_\Delta,x_{u_i},x_\ell)\,\epsilon_{abc}\left(\overline{u_a^C}\gamma^\mu P_L d_b\right)\left(\overline{d_c^C}\gamma_\mu P_L \nu\right)\,.$$

Box function

$$J(x_\Delta, x_{u_i}, x_\ell) = \sqrt{x_{u_i} x_\ell} \quad \left[\frac{(x_\Delta - 4) x_\Delta \log x_\Delta}{(x_\Delta - 1)(x_\Delta - x_i)(x_\Delta - x_\ell)} + \frac{(x_{u_i} - 4) x_{u_i} \log x_{u_i}}{(x_{u_i} - 1)(x_{u_i} - x_\Delta)(x_{u_i} - x_\ell)} \right.$$
$$\left. + \frac{(x_\ell - 4) x_\ell \log x_\ell}{(x_\ell - 1)(x_\ell - x_\Delta)(x_\ell - x_\ell)} \right]$$

there are two regimes

for top in the loop
$$J(x_\Delta, x_t, x_\ell) = \frac{\sqrt{x_t x_\ell}}{x_\Delta - x_t} \left[\frac{x_\Delta - 4}{x_\Delta - 1} \log x_\Delta - \frac{x_t - 4}{x_t - 1} \log x_t \right]$$

below m_W scale
$$J(x_\Delta, x_{u_i}, x_\ell) = \frac{\sqrt{x_{u_i} x_\ell}}{x_\Delta} \left[\frac{x_\Delta - 4}{x_\Delta - 1} \log x_\Delta + \frac{4}{x_{u_i} - x_\ell} (x_\ell \log x_\ell - x_{u_i} \log x_{u_i}) \right]$$

Fierz transformation

$$\epsilon_{abc} \left(\overline{u_a^C} \gamma^\mu P_L d_b \right) \left(\overline{d_c^C} \gamma_\mu P_L \nu \right) \; = \; -\epsilon_{abc} \left(\overline{d_b^C} \gamma^\mu P_R u_a \right) \left(\overline{d_c^C} \gamma_\mu P_L \nu \right) = 2\epsilon_{abc} \left(\overline{d_b^C} P_L \nu \right) \left(\overline{d_c^C} P_R u_a \right)$$

also $\quad (\overline{d_b^C} P_L \nu) = (\overline{\nu^C} P_L d_b) \qquad 2\epsilon_{abc} \left(\overline{d_a^C} P_R u_b \right) \left(\overline{\nu^C} P_L d_c \right) \to 2\overline{\nu^C} \left\langle M^0 \,\middle|\, (du)_R d_L \,\middle|\, p \right\rangle$

Lattice study of the non-perturbative matrix element:

Operator basis for proton decay

$$
\begin{aligned}
O^{(1)}_{abcd} &= (D^i_a, U^j_b)_R (q^{k\alpha}_c, l^\beta_d)_L \epsilon^{ijk}\epsilon^{\alpha\beta} \\
O^{(2)}_{abcd} &= (q^{i\alpha}_a, q^{j\beta}_b)_L (U^k_c, l_d)_R \epsilon^{ijk}\epsilon^{\alpha\beta} \\
\tilde{O}^{(4)}_{abcd} &= (q^{i\alpha}_a, q^{j\beta}_b)_L (q^{k\gamma}_c, l^\delta_d)_L \epsilon^{ijk}\epsilon^{\alpha\beta}\epsilon^{\gamma\delta} \\
O^{(5)}_{abcd} &= (D^i_a, U^j_b)_R (U^k_c, l_d)_R \epsilon^{ijk},
\end{aligned}
$$

Lorentz symmetry

$$\langle PS; \vec{p}| \mathcal{O}^{R/L\,L} | N; \vec{k}, s\rangle = P_L[W_0^{R/L\,L}(q^2) - i\not{q} W_q^{R/L\,L}(q^2)] u_N(\vec{k}, s)$$

soft pion theorem

$$
\begin{aligned}
W_0^{RL}(p \to \pi^0) &= \alpha(1+D+F)/\sqrt{2}f \\
W_0^{LL}(p \to \pi^0) &= \beta(1+D+F)/\sqrt{2}f
\end{aligned}
$$

from the chiral lagrangian

$$D + F = g_A$$

D=0.8; F=0.47

lattice calculations [Aoki et al (2007)]

$$\alpha P_R = - < 0 | O^{LR}_{udu} | p > \qquad -\alpha = 0.0100(12)(14)(6)\ \mathrm{GeV}^3.$$

$$\boxed{\langle \pi^+ \,|\, (ud)_R d_L \,|\, p\rangle \;=\; P_L \left[\alpha(1+D+F)\frac{1}{\sqrt{2}f}\right] u_p}$$

Low energy phenomenology establish following texture of the Yukawa matrix

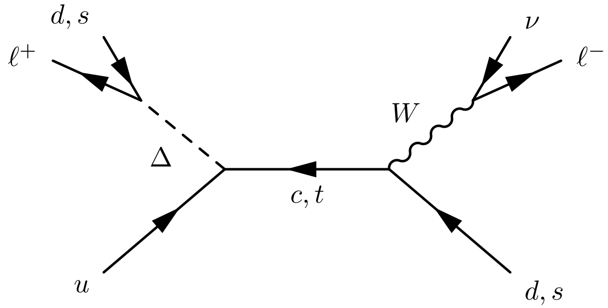
$$Y_{ld} \approx \begin{pmatrix} 0 & 0 & 0 \\ \blacksquare & 0 & 0 \\ \bullet & \bullet & \bullet \end{pmatrix}, \quad \begin{pmatrix} 0 & 0 & 0 \\ 0 & \blacksquare & 0 \\ \bullet & \bullet & \bullet \end{pmatrix}, \quad \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & \blacksquare \\ \bullet & \bullet & \bullet \end{pmatrix}$$

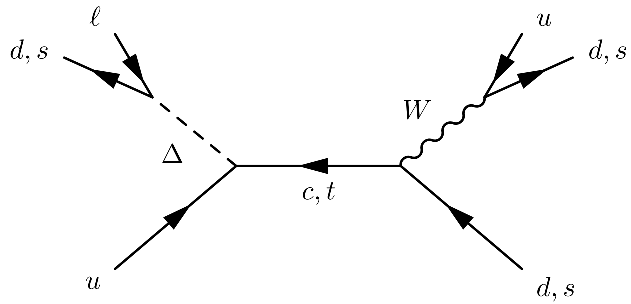
$$\sum_{i=c,t} \sum_{j=d,s,b} [U_C^\dagger (Y^{10*} - Y^{10\dagger}) U_C^*]_{ui} V_{id} V_{uj}^* [D_C^\dagger Y^{\bar{5}\dagger} E_C^*]_{j\ell} J(x_\Delta, x_{u_i}, x_{d_j}) \sim (\Gamma(p \to \pi^0 e^+))^{1/2}$$

or μ

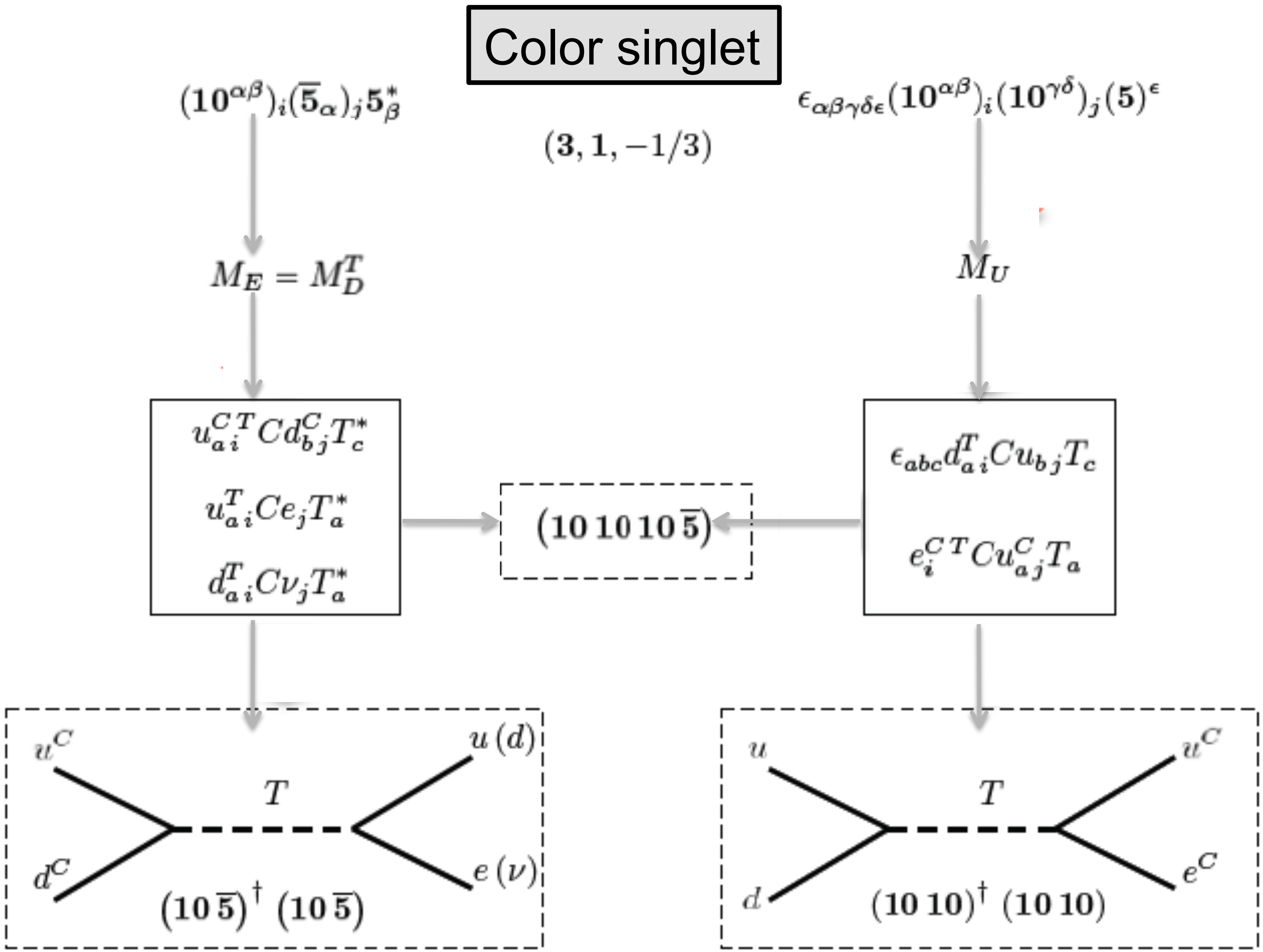
either this or this are equal 0, or there is some fine tuning making this sum to be 0!

Tree level dimension-9 operator





$$
\begin{aligned}
\mathcal{L}_9 \quad = \quad & \frac{2 G_F V_{id'}}{m_{u_i} m_\Delta^2} \overbrace{\left[U_C^\dagger (Y^{10*} - Y^{10\dagger}) U_C^* \right]_{ui} V_{id} V_{uj}^* \left[D_C^\dagger Y^{\bar{5}\dagger} E_C^* \right]_{d\ell}}^{\approx 0} \\
& \times \epsilon_{abc} \left(\overline{u_a^C} \gamma^\mu P_L d_b' \right) \left(\overline{d_c^C} P_R \ell \right) \left\{ \begin{array}{l} V_{ud''}^* \left(\overline{d''} \gamma_\mu P_L u \right) \\ \left(\overline{\ell'} \gamma_\mu P_L \nu \right) \end{array} \right. \quad .
\end{aligned}
$$



Color singlet
$(\mathbf{10}^{\alpha\beta})_i(\overline{\mathbf{5}}_\alpha)_j\mathbf{5}^*_\beta$
$(\mathbf{3},\mathbf{1},-1/3)$
$\epsilon_{\alpha\beta\gamma\delta\epsilon}(\mathbf{10}^{\alpha\beta})_i(\mathbf{10}^{\gamma\delta})_j(\mathbf{5})^\epsilon$
$M_E = M_D^T$
M_U
$u^{C\,T}_{a\,i} C d^C_{b\,j} T^*_c$
$u^T_{a\,i} C e_j T^*_a$
$d^T_{a\,i} C \nu_j T^*_a$
$(\mathbf{10}\,\mathbf{10}\,\mathbf{10}\,\overline{\mathbf{5}})$
$\epsilon_{abc} d^T_{a\,i} C u_{b\,j} T_c$
$e^{C\,T}_i C u^C_{a\,j} T_a$
u^C
d^C
T
$u\,(d)$
$e\,(\nu)$
$(\mathbf{10}\,\overline{\mathbf{5}})^\dagger\,(\mathbf{10}\,\overline{\mathbf{5}})$
u
d
T
u^C
e^C
$(\mathbf{10}\,\mathbf{10})^\dagger\,(\mathbf{10}\,\mathbf{10})$

Color triplet (3,3,-1/3)

1107.2933 Vecchi:
baryon number conservation
low energy phenomenology

$$\phi = \begin{pmatrix} \frac{1}{\sqrt{2}}\phi_{-\frac{1}{3}} & \phi_{+\frac{2}{3}} \\ \phi_{-\frac{4}{3}} & -\frac{1}{\sqrt{2}}\phi_{-\frac{1}{3}} \end{pmatrix}$$

$$\mathcal{L}_{\mathrm{C\&W-triplet}} \equiv \mathcal{L}_{\mathrm{SM}} + \mathrm{Tr}(D_\mu \phi^\dagger D^\mu \phi) + \lambda_{ij} \overline{Q_i^c} \epsilon \phi Q_j + \mathrm{hc} - V_{\phi^2} - V_{\phi^4}.$$

$$\begin{aligned} \mathcal{L}_{\mathrm{Yukawa}} &= \lambda_{ij} \overline{Q_i^c} \epsilon \phi Q_j + \mathrm{hc} \\ &= \lambda_{ij} \left[-\sqrt{2}\, \overline{u_i^c} \phi_{-\frac{1}{3}} d_j - \overline{d_i^c} \phi_{+\frac{2}{3}} d_j + \overline{u_i^c} \phi_{-\frac{4}{3}} u_j \right] + \mathrm{hc.} \end{aligned}$$

anti-symmetric

no ΔF =2 effective operators et tree level!

$$\begin{aligned} m_{1/3}^2 &= M_\phi^2 + \kappa_1 \frac{v^2}{2} \\ m_{4/3}^2 &= m_{1/3}^2 + \kappa_2 \frac{v^2}{2} \\ m_{2/3}^2 &= m_{1/3}^2 - \kappa_2 \frac{v^2}{2} = 2m_{1/3}^2 - m_{4/3}^2. \end{aligned}$$

$$
\begin{aligned}
\mathcal{L}_{\text{Yukawa}} &= \lambda_{ij}\overline{Q_i^c}\epsilon\phi Q_j + \text{hc} \\
&= \lambda_{ij}\left[-\sqrt{2}\,\overline{u_i^c}\phi_{-\frac{1}{3}}d_j - \overline{d_i^c}\phi_{+\frac{2}{3}}d_j + \overline{u_i^c}\phi_{-\frac{4}{3}}u_j\right] + \text{hc.}
\end{aligned}
$$

it is like a (3,1,-1/3)

it is like a (3,1,4/3)
in SU(5)XU(1)

as (3,1,-4/3)

Proton decay implies a (3,1,-1/3) to be very heavy
≈ M_{GUT} !

Probe of baryon number violation at LHC
Top BNV

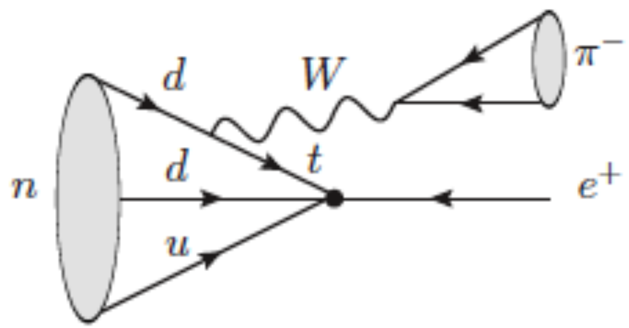
1107.3805

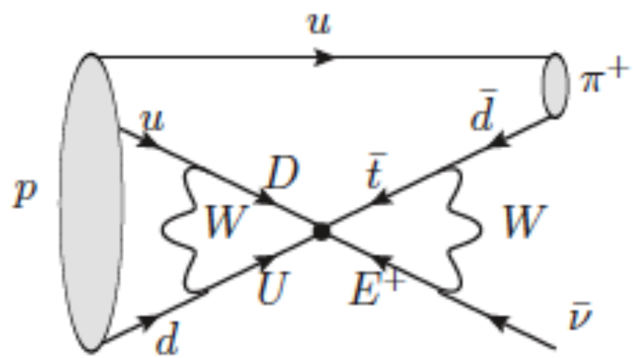
Zhe Dong[a], Gauthier Durieux[b], Jean-Marc Gérard[b], Tao Han[a], Fabio Maltoni

$$O^{(s)} \equiv \epsilon^{\alpha\beta\gamma}[\overline{t^c_\alpha}(aP_L + bP_R)D_\gamma][\overline{U^c_\beta}(cP_L + dP_R)E],$$
$$O^{(t)} \equiv \epsilon^{\alpha\beta\gamma}[\overline{t^c_\alpha}(a'P_L + b'P_R)E][\overline{U^c_\beta}(c'P_L + d'P_R)D_\gamma], \tag{2}$$

processes

$$t \xrightarrow{\text{BNV}} \overline{U}\,\overline{D}\,E^+ \quad \text{(decay)}$$
$$U\,D \xrightarrow{\text{BNV}} \bar{t}\,E^+ \quad \text{(production)}$$





Conclusions

• Forward-backward asymmetry in $t\bar{t}$ production can be explained by exchange of Δ;

• Contribution of Δ to muon anomalous magnetic moment is positive for large $Y_{\mu q}$;

• $D^0 - \bar{D}^0$ mixing and single top production impose $g_{uc} \sim 0.1$ $g_{ct} \sim 0.001$;

• LFV and FCNCs in the down-quark and charged lepton processes together with $(g-2)_\mu$ lead to texture :

$$Y \sim \begin{pmatrix} 0 & 0 & 0 \\ \blacksquare & 0 & 0 \\ \bullet & \bullet & \bullet \end{pmatrix}, \quad \begin{pmatrix} 0 & 0 & 0 \\ 0 & \blacksquare & 0 \\ \bullet & \bullet & \bullet \end{pmatrix}, \quad \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & \blacksquare \\ \bullet & \bullet & \bullet \end{pmatrix}$$

• Direct search: second generation leptoquark

$$\Delta \to \mu q \quad \Delta \to ut \qquad m_\Delta \simeq 380 - 600 \ \mathrm{GeV}$$

- low energy phenomenology fixed the Yukawa couplings;

- we determined texture of the up quark mass matrix;

- we showed that symmetric scenario for the Yukawa couplings of leptoquarks to down-quarks and charged leptons is not compatible with the constraints due to the presence of light Δ;

- other scenario: e.g. SO(10) with 120, 126 and 10….

- proton decay operators induced via scalar exchange are very model dependent;

- even if proton decay is absent at tree level there are dangerous box-diagram induced contributions;

- BNV processes can be eventually tested in top decays at LHC.

Thank you!